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Team Reports: Virtual Planetary Laboratory

Virtual Planetary Laboratory
Executive Summary
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THE VIRTUAL PLANETARY LABORATORY

Laying the Scientific Foundation for the Search for Life Beyond the Solar System

Because of the vast distances to even the nearest stars, the search for life outside our solar system will be undertaken using astronomical, or “remote−sensing” techniques. While much can be learned about a planet discovered around another star based on the characteristics of the host star and the planet's position in its solar system, spectroscopy is still our most powerful technique for extrasolar planet characterization. The research of the NASA Astrobiology Institute's Virtual Planetary Laboratory (VPL) uses computer models of terrestrial planets to understand the nature and potential range of remote−sensing spectroscopic signs of planetary habitability and life which might be encountered by future planet detection and characterization missions.

Terrestrial Planet Detection and Characterization Missions

There are several missions currently in the planning stage to search for and characterize extrasolar terrestrial planets, and all have planned spectroscopic capability. These missions include the two NASA Terrestrial Planet Finder (TPF) Missions and the European Space Agency (ESA) Darwin mission. The first TPF mission, TPF−C, slated for launch in 2014, will use coronographic technology to block the considerable light from the parent star and reveal the much fainter orbiting planet. TPF−C is designed to detect and characterize extrasolar terrestrial planets via disk−averaged visible light reflected from the planet, and will be well suited to obtain good estimates of the amounts of atmospheric gases detected at visible wavelengths (e.g. O_2 , H_2O and CH_4), and to discriminate between different planetary surface types. The TPF−I and Darwin missions are slated for launch no later than 2020, and will use free−flying spacecraft to enable an interferometric technique for nulling the light from the central star, to detect and characterize an orbiting planet. TPF−I/Darwin will operate at mid−infrared wavelengths, within the range 6−18 m m, and will be sensitive to thermal radiation emitted by the warm planet. TPF−I/Darwin will be sensitive to the overall trace gas composition of the atmosphere, including greenhouse gases (CO_2, H_2O, SO_2) and many potential gas biosignatures (e.g. O_3, CH_4, N_2O and a number of sulfur compounds). If the planet's surface is not hidden by clouds, TPF−I can also provide information required to infer atmospheric and surface temperatures. The complementary information provided by TPF−C and TPF−I/Darwin, can provide a robust indicator of the planet's size, and when combined with information on planetary mass provided by the Space Interferometer Mission (to launch in 2009), will provide a powerful dataset for comprehensive characterization of terrestrial planets beyond our solar system, including the search for global planetary characteristics that are signs of life. Beyond the TPF and Darwin missions, NASA envisages an even more ambitious mission, Life Finder, whose goal is to provide even more detailed spectroscopic study of terrestrial planets found by the previous missions.

The VPL Research Goals, Astrobiology, and NASA

The VPL is a suite of computer models for simulating the plausible range of atmospheric and surface compositions and climates for terrestrial planets. The objective of this project is to provide the fundamental research needed to support the remote−sensing detection of life, by improving our understanding of the use of spectra to discriminate between extrasolar planets with and without life. This work is most directly relevant to the Astrobiology Roadmap Goals 1 and 7, on the nature of planetary habitability and the remote−sensing signs of life. However, work undertaken as part of the VPL planetary modeling effort also touches on aspects required to understand the Earth's early biosphere (Goal 4), biochemical adaptation to extreme environments (Goal 5), and environmental changes and the cycling of elements by ecosystems (Goal 6). In addition, the work of the VPL provides valuable results to guide the design and search strategies for future NASA planet detection and characterization missions, and VPL scientists also provide two−way communication between astrobiology and NASA mission concepts in Earth and planetary exploration.

The Virtual Planetary Laboratory – Yr 6 Research Projects

Building the VPL: Tasks 1−7. This year, the VPL team continued its efforts to develop and combine computer models of planetary processes into a series of progressively comprehensive terrestrial planet models, and significant milestones, particularly in model integration, were achieved. The completed VPL model suite will provide the capability to model terrestrial planet environments in a self−consistent fashion, and output the spectral appearance of these environments to remote−sensing observations. The resultant models are being applied to a number of scientific questions on the environments of early Earth and extrasolar terrestrial planets.

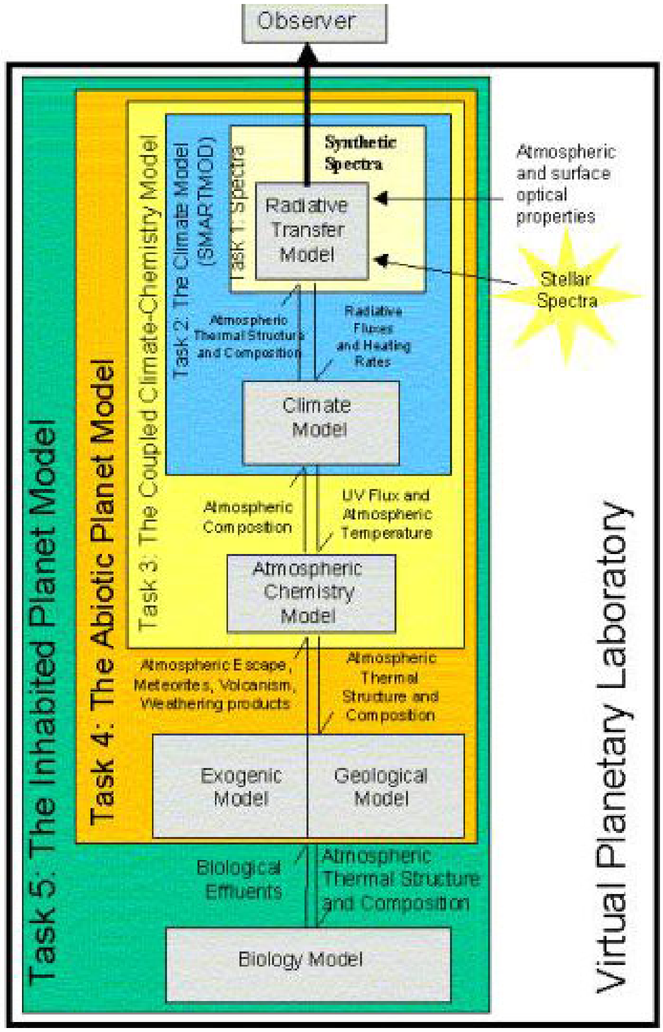

Figure 1: The suite of radiative transfer, climate, chemical, geological, and biological component models are shown as boxes, and their interactions with each other are shown as arrows. The information transferred between these component models is labeled at each interface. The order in which these component models are coupled to each other during the course of building the VPL is specified by the Task number. The radiative transfer, climate and atmospheric chemistry models already exist, and the remaining models are under development by our team. At each task development stage the model can be used to generate synthetic spectra to derive required capabilities for astronomical instrumentation.

This effort is characterized by 5 successive component tasks, the supporting task of spectral database compilation, and the overarching task of model integration. These tasks and highlighted accomplishments are:

Task 1: Spatially−resolved models of terrestrial planets

This task develops sophisticated spatially and spectrally−resolved models of planets in our own Solar System using radiative transfer models, and observed physical properties and environmental data. The reflected solar and emitted infrared spectra generated by models are then averaged across the visible disk of the planet to produce a “disk−averaged” result, which mimics the type of results anticipated from TPF. Research highlights for this year include completion of the Mars and Earth models, and the production and analysis of disk−averaged 0.1 to 160 µm spectra, light−curves, spectral variability as a function of viewing angle and season, and simulations of an increasingly frozen Mars, and an increasingly cloudy/forested/oceanic Earth.

Task 2: A Climate Model for Extrasolar Terrestrial Planets

This task develops a versatile one−dimensional (1−D) terrestrial planet climate model to yield a globally−averaged description of the surface temperature and vertical temperature distribution that is in thermal equilibrium with the imposed stellar flux from the host star, planetary orbital properties, and the surface and atmosphere composition and optical properties. These temperature distributions are crucial for understanding both the habitability and detectability (at mid−infrared) wavelengths of biosignatures in the disk−averaged spectrum of the planet. Progress this year included the integration of generalized and computationally improved radiative, convective and conductive transport algorithms into the existing climate model to increase computational speed. The resultant model was used to produce annual cycles of soil and atmospheric temperature for a Mars−like planet.

Task 3: A Chemistry Model for Extrasolar Terrestrial Planets

This task focuses on the development of a generalized, yet comprehensive, photochemical model for terrestrial planet atmospheres. This model will interact with the climate model described in Task 2, to create a self−consistent climate−chemical model. This year the model was updated to operate in our Linux test environment, and work was started on the creation of a master reaction file for terrestrial planets and the software to access user−specified reaction sets to describe different classes of planetary atmospheres .

Task 4: The Abiotic Planet Model: The Upper and Lower Boundary Conditions on the Atmosphere

This task develops models of processes at the upper and lower boundaries of the coupled climate−chemical model, including exogenic mass fluxes (dust/meteors/asteroids, atmospheric loss) and surface−atmosphere interactions (chemical weathering, outgassing). When integrated with the climate−chemical model, this module will produce a self−consistent model of a terrestrial planet without life. This past year saw the addition of melt−generation (for predicting mantle volatile loss to the atmosphere) into the planetary interior/plate tectonics model. Progress was also made on reactive transport models for rock weathering, to help constrain the evolution of mineralogies of other habitable planetary surfaces and their volatile fluxes. Work also continued on a model for hydrodynamic loss processes from planetary atmospheres. Research results included the use of kinetics to predict formation of siderite in soils that develop under slightly oxic conditions, which is contrary to thermodynamic predictions. These results reinforce the conclusion that paleosols formation before 2.4Gya occurred under an atmosphere with less than 30 times the present level of CO_2 . Reactive transport modeling also showed that black shale weathering is an important factor in regulating Earth's atmospheric oxygen composition during the Phanerozoic.

Task 5: The Inhabited Planet Model: The Life Modules

This task provides computer models of life's interaction with the planetary environment for integration with the Task 4 model. Progress this year includes the completion of life module components, including microbial mats and Archean ecosystem models, and initial improvements to existing Earth land surface models to predict vegetation albedos. Our Archean ecosystem modeling indicates that the Archean biosphere was capable of generating methane surface fluxes comparable to those of modern Earth, which would have been large enough to keep the early Earth warm. These results emphasize that life can affect the climate and atmosphere of extrasolar planets in ways that can be detected by instruments such as TPF, even in the absence of oxygenic photosynthesis.

This task also includes a field trip component to analyze life in highly alkaline aquifers and springs that are associated with terrestrial serpentinizing bodies, providing a model system for life at the surface of young terrestrial bodies. Research highlights this year include completion of the initial survey of the genetic diversity of microbes, which show considerable diversity, despite the extreme lack of nutrients and high pH (>11.5).

Task 6: Spectroscopic Databases to Support Extrasolar Planet Modelling: Stellar and Molecular

This task focuses on collecting and preparing full−wavelength, continuous stellar spectra for use by planetary climate and chemistry models. This year we worked on spectra of quiescent and active M stars, with spectra now available for two M stars, AD Leo and GJ643. These spectra are currently being used to simulate the nature and detectability of characteristics of Earth−like planets around quiescent M stars. Future work will include the less active M dwarf spectra, and a full time−dependent characterization for a more active M−star.

We also continued development of the molecular spectra database, which is a collection of line lists and absorption cross−sections for 61 molecules of interest to astrobiologists and planetary scientists. The database was made public this year at http://vpl.ipac.caltech.edu/spectra/ .

Task 7: The Virtual Planetary Laboratory: Synthesis and Architecture

This task focuses on interfacing and integration of the core model components to produce the VPL planetary models described in Tasks 3−5. This year, significant progress was made on interface design, with the development of an Application Programming Interface (API) and a central VPL model database. This allows current code components (and all future components) to access model results from the full range of VPL tools, especially those that operate on very different planetary timescales. As a major milestone, the first full VPL coupled−climate−chemical model run was executed at the very end of this reporting period. As our first step toward the community tool that VPL is intended to be, we also developed a structured data format and a web front end for the Task 2 climate code to allow the user to enter a planetary “state” of parameters for configuring the climate model runs, and to enable execution of VPL models from centralized databases over the Internet.

In addition to work on the VPL modeling suite, we have also worked to improve our understanding of the characterization of terrestrial planets from disk−averaged spectra. This work has been undertaken in three distinct research areas:

Sensitivity to Planetary Characteristics in Disk−Averaged Spectra

The completion of the Mars and Earth Task 1 models allowed us to explore the detectability of local features in the disk−averaged spectrum, as a function of viewing angle, solar illumination, and surface type. First results from the Mars model indicate that the presence of the Martian poles, and seasonal changes in polar ice coverage, could be detected in disk−averaged spectra at both visible and Millimeter Imaging Radiometer (MIR) wavelengths. Simulations with an increasingly frozen Mars indicated that the effect of the ice cap is most easily detected in the wavelength range 8−13.5 m m, where the wavelength dependent emissivity of CO_2 ice produces a strong spectral feature.

Earth−like Planets Around Other Stars

Building on last year's coupled climate−chemical modeling of Earth−like planets around F, G and K stars, we are now using similar models to explore the detectability of characteristics for Earth−like planets orbiting M stars, which are typically highly variable. Our current simulations use the observed time−averaged spectra of two M stars and a quiescent, modeled M star. For 1PAL Earth−like atmospheres, our results show that planets with the modern day Earth surface methane flux show an atmospheric abundance that is relatively high due to reduced tropospheric OH densities, which increases the atmospheric lifetime, even in these O_2 −rich atmospheres. Consequently even small surface fluxes of methane could be highly detectable around M stars. Our models also show that ozone, photochemically derived from O2, is detectable in Earth−like planets around non−active M stars with photospheric temperatures in excess of 3400K. Below that stellar temperature threshold, O3 is not detectable. We are currently developing a time−dependent climate−photochemical model to determine how the flux variability of M stars would affect the lifetime and detectability of planetary biosignatures.

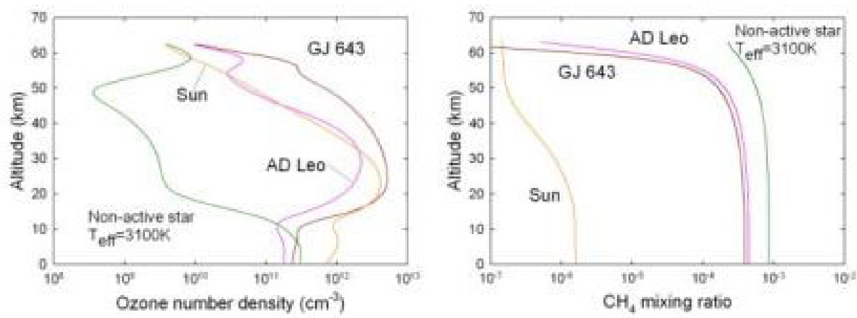

Figure 2: Coupled climate−chemsitry model simulations of the atmospheric vertical distribution of ozone and methane in Earth−like planets around the active, but time−averaged M−stars AD Leo and GJ 643, compared with the value for the Earth (around the Sun) and a non−active modeled M star with an effective temperature of 3100K. While the ozone show similar abundances and distribution to the Earth, except in the case of the planet around the 3100K star, all the M−stars show enhanced atmospheric CH_4.

Analysis and Discrimination of TPF Planetary Spectra Using Artificial Neural Network Techniques.

To determine the scientific impact of trade−offs in instrument characteristics (e.g. wavelength coverage, spectral resolution, and signal−to−noise (S/N)) for spectral characterization of terrestrial planets, this task focuses on using Artificial Neural Networks (ANNs) to determine instrumentation limits for reliable classification of spectra. As the test set, we have used UV−FIR planetary spectra generated by the VPL and convolved these with slit functions and a simplistic noise model to produce spectra with a range of spectral resolutions and S/N levels. With our simplistic noise model, the ANNs clearly discriminate spectra at very modest resolutions and S/N. Ongoing work involves expanding the test set to other planetary types, and working with the TPF design teams to get more realistic noise models.

VPL Education and Public Outreach

VPL is providing budget and scientist support to develop the “Create a Planet” module of the AstroVenture interactive website for middle school students. AstroVenture highlights NASA careers and astrobiology research. VPL is also funding in−service teachers to earn graduate credits taking the “Astrobiology On−line Course for Teachers” in informal education, and providing support for the California Academy of Science. We delivered field photos and a profile of Dr. Kress for the museum's astrobiology exhibit. Additionally, there are numerous E/PO efforts by Dr. Meadows and VPL scientists, and an online astrobiology course provided by Dr. Siefert at Rice University.